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THE PHYSICAL STRUCTURE OF TURBULENT FLAMES,(U)
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The Physical Structure of Turbulent Flames

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17th AEROSPACE SCIENCES MEETING

New Orleans, La./January 15-17, 1979

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THE PHYSICAL STRUCTURE OF TURBULENT FLAMES

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Abstract

This paper reports on measurements made in the mixing region of an axisymmetric turbulent propane/air jet issuing from a round nozzle into a low-velocity, low-turbulence intensity, unconfined co-flowing airstream. The exit velocity of the jet fluid and its turbulence intensity are sufficiently low to allow the formation of ring vortices within the mixing layer, bounded, on the inside, by the potential core of the jet and, on the outside, by the secondary airstream. High speed cine films show evidence of formation of vortices and flamelets at the interfaces. The changes in shape, movement and coalescence downstream of the nozzle are examined. Measurements of fluctuating velocity are made by a single particle-counting forwardscatter laser anemometer. Fluctuating temperature is measured with micro-thermocouples with *in situ* measurement of time constant and direct compensation by digital signal recording and analysis. Variation in location and amplitude of peaks of velocity and temperature traces are directly associated with flame structures recorded by film. Signals from all probes are acquired and processed by PDP-8 and PDP-1103 Digital Equipment Corporation computers. Comparisons between cold and burning jets show that the essential physical processes of transition are the same for both cases, i.e. vortex growth, coalescence, three dimensional breakdown and turbulent large eddy formation. The major effect of combustion in the initial region is increased viscous damping of interface instabilities which greatly increases both the transition and potential core lengths of the jet.

Introduction

Many fundamental experimental studies have been made of non reacting turbulent shear flows following the development of reliable hot wire anemometer techniques. In recent years emphasis has been placed on the importance of not only measurement accuracy, but also the accuracy with which the initial and boundary conditions of the flows are known and controlled. With some notable exceptions, and primarily because of the great difficulty of making any measurements at all, turbulent flows with reaction have not been investigated in detail. An objective of this investigation is to map the flow field of axisymmetric gas diffusion flames originating from low turbulence conditions at the nozzle and thin laminar nozzle boundary layers. The natural instability and transition of the mixing layer is examined for the flame case, in which initial flame stabilization and combustion occurs at a well defined laminar interface. Comparisons are made with the corresponding non-burning jets to determine the interaction between combustion and the transition process. Experiments with non-reacting flows have shown the importance of the relatively organised and repetitive physical event and eddies. An additional objective of the experiment is to examine the flow structure with emphasis on the roles of larger scales of motion in the transitional and turbulent regions of flames.

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Turbulent jet flames are dependent upon the physical structure of turbulent jets with the added perturbations caused by chemical reaction and heat release. In gaseous fuel jets dependent upon diffusion of air from the surroundings, the flame characteristics, combustion performance and formation and destruction of pollutants are governed by mixing processes. Mixing occurs across interfaces separating the jet from surrounding fluid and combustion is restricted to regions where the mixing ratio is within the limits of flammability. The reaction zone and flame fronts represent regions where mixing has been completed on the molecular scale and the criteria for flame stabilization have been satisfied. Flame propagation and stabilization is dependent upon the matching of burning velocity with local flow velocity and heat released by chemical reaction must exceed heat convection away from the flame.

An extensive research program has been initiated with the aim of understanding and describing the mechanics of turbulent structure and mixing in jet flames. The case of a free round vertical jet of gaseous fuel injected into a low velocity, low turbulence intensity, free main airstream has been selected as one of the 'simplest' configurations for detailed study, but it also has wide practical relevence. This configuration provides an initial mixing region, bounded by an inner potential core and an outer uniform flow, which can also be related to the two-dimensional mixing layer. For jets with low initial turbulence intensity and laminar nozzle boundary layers, the mixing layer is initially laminar and is dominated by viscous forces. For the cold case these conditions allow the formation of clear and distinct ring vortices, which can be seen to separate, move downstream, become unstable and break up to provide the 'kernels' of turbulent eddy structures.

Roshko and co-workers[1] have shown by flow visualization and by measurement that interfaces in two-dimensional mixing layers can roll up to form vortices which move downstream, coalesce and grow in size with the increase in width of the mixing layer. Yule[2] has investigated late transitional and turbulent flows in the mixing layer region of a round jet for a range of Reynolds numbers by using flow visualization and hot wire techniques. He showed clearly the interaction and coalescence of vortex rings in the transition region. The transition region is characterized by the growth of three-dimensional flow due to wave instability of the cores of the vortex rings. The merging of these distorted vortices produces large eddies, which can remain coherent up to the end of the potential core region of the jet. Turbulent eddies were found to differ significantly from the

ring vortices, and were found to be three-dimensional and contain irregular small-scale turbulence. The averaged structure of turbulent eddies is, however, similar in cross-section to that of a vortex ring.

The investigation reported in this paper focuses attention on the formation of vortices and eddy structures in the initial region of the mixing layer of transitional free jet flames. High-speed cine photography is used to identify the location of flame fronts and regions of burning. Laser anemometer traverses permit measurement of instantaneous and average velocity distributions across the potential core region and through the mixing layer. Comparisons of turbulent jet structure and development are made for burning and non-burning conditions. Temperature distributions are measured by high-frequency response thermocouples and probability density functions based on velocity are shown for burning and non-burning conditions.

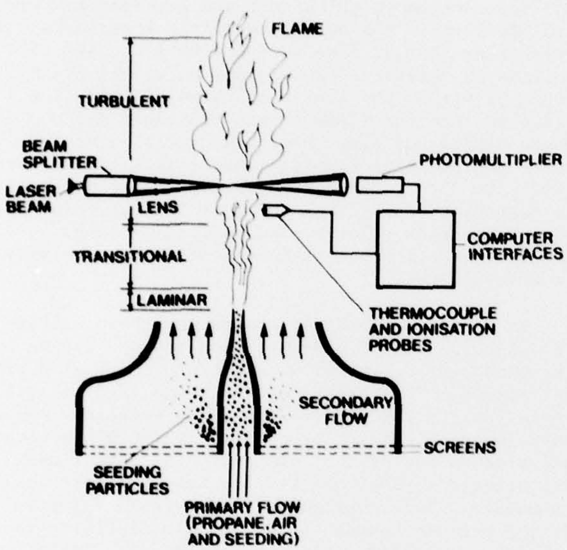


Fig. 1. Turbulent axisymmetric jet flame in co-flowing free airstream.

Experimental Apparatus and Instrumentation

A schematic view of the experimental apparatus is shown in Fig. 1. The central jet has an exit nozzle diameter of 25.4 mm, through which a mixture of propane and air is injected. The surrounding airstream passes through a set of screens and emerges through a square nozzle of 400 mm width. The jet exit velocity, $U_j = 6.3$ m/s with $Re_j = 10^4$. The surrounding air velocity, $U_s = 0.73$ m/s. Turbulence levels in both the jet and surrounding exit streams are less than 1%. The fuel/air equivalence ratio of the propane/air premixed flow is 10.4. The total visible flame length is 1.5 m. The complete burner can be traversed in the vertical and horizontal directions. Silicone dioxide seeding particles, 0.1 μm diameter, are added to both the jet and surrounding streams as indicated in Fig. 1. The seeding densities of both streams were made equal to minimise biasing effects.

A Hadland high-speed cine camera, with a maximum framing rate of 10,000 fps, is used to study the flame structure. This camera can also record oscilloscope traces directly on film from the laser anemometer and the thermocouple, enabling peaks in velocity and temperature to be directly associated with the passage of discrete eddy structures. Velocity is measured by a laser anemometer, using a Spectra Physics 164 Argon Ion 1W laser. A single particle counting system is used with dual count validation logic. After signal processing velocity as a function of real time is recorded, via a PDP-1103 micro-processor, on the disk of a PDP-8E mini-computer. This system allows measurement of mean and rms velocity from 40,000 signals at 2 K Hz, probability density functions, conditional sampling and correlations are also derived. Temperature is measured by fine wire Pt/PtRh thermocouples (50 μm). Time constants are measured directly in the flame by introducing a heating pulse and measurements as a function of real time are also recorded on the disk of the PDP-8E computer with subsequent digital compensation based on the measured time constant[3].

Transitional Flow

By definition, in transitional flow, viscous forces are significant and flow structure is Reynolds number dependent. In the two-dimensional mixing layer there is some evidence[4] that transition can be postponed for long distances downstream, provided that the bounding streams have very low turbulence intensities. As soon as the turbulence intensity is increased, and also in the far downstream region, the turbulent flow predominates but it has not been clearly demonstrated that the turbulent flow is truly fully developed so that it is self preserving and Reynolds number independent. In round jets the boundary between the potential core and mixing layer converges towards the axis and beyond the potential core region, $x/D > 4$, the interaction of the mixing layer results in the spreading of vorticity across the whole jet. In theory, fully developed self preserving turbulent flows, which are Reynolds number independent and self-similar in all turbulence characteristics, may be achieved both in the turbulent mixing region and also far downstream. However, in practice, exact self preservation is not found. The detailed investigations by Yule[2] show that the transitional region was characterized by the presence of ring vortices and coalescence, as shown by peak frequency halving in measured power spectra of velocity. Measurements of fluctuating velocity components show that $(\overline{v^2})^{\frac{1}{2}}$ increases to a peak near the orifice and then decreases more slowly to a nearly constant value; the circumferential component $(\overline{w^2})^{\frac{1}{2}}$ increases gradually to its turbulent value, which is reached at a similar distance downstream; the axial component $(\overline{u^2})^{\frac{1}{2}}$ increases rapidly to reach its turbulent value considerably before the other intensity components. The asymptotic values of the three intensity components were the same to within 15% with a value of $(\overline{u^2})^{\frac{1}{2}}/U_j$ between 0.14 and 0.15. These characteristic features of transitional flow, combined with flow visualisation and conditional sampling allowed Yule to determine a schematic picture of the physical structure of transitional jets. An important finding was that large eddies in the turbulent flow were derived from the breakdown and interaction of the transitional vortices.

The gradual growth of three-dimensionality during transition was found to be due to secondary wave instabilities of the cores of the vortex rings. Successive rings tend to have core waves

in similar azimuthal positions and this results in appearance of axial streaks, or striations, in many flow visualizations of jets, e.g. the Schlieren photographs of Bradshaw[5]. It is important to know the effect of this physical structure on the flame structure for the case of two gases reacting at the interface separating them. Conversely, it is important to know how reaction modifies this transitional structure, which is so clearly found in the non-reacting case.

The kinematic viscosity of gases is very temperature-sensitive and, even though there are no accurate measurements of viscosity at flame temperatures, kinematic viscosity varies approximately as $T^{3/2}$. When comparisons are made between jet flows under non-burning and burning conditions, account needs to be taken of the increase in kinematic viscosity by a factor of up to 20 as temperature increases from cold flow at approximately 300 K to burning flow at approximately 2000 K. This large-scale increase in kinematic viscosity can be expected to produce a significant change in the transitional flow regime compared with cold turbulent jets.

Under burning conditions, the effects of viscosity should persist to much higher Reynolds numbers (based on cold conditions at the nozzle exit). There is evidence that turbulent non-burning jets can be almost completely laminarized after ignition, for example, Takeno and Kotani[6] studied hydrogen jets qualitatively at a Reynolds number of 1240 with a corresponding flame Reynolds number of 227 and acetylene jets of Reynolds number 1240 with a corresponding flame Reynolds number of 24. Schlieren photographs showed the transition to turbulence in the cold jets, while the flame jets appeared to be laminar throughout the whole flow field. The other major phenomenon that needs to be considered in differentiating between the cold and burning cases is dilatation caused by the density changes accompanying reaction. It is important to quantify and differentiate between the dilatation and viscosity effects.

The Mixing Layer

The mixing layer is shown schematically in Fig. 2. It originates at the nozzle lip, spreading outwards radially and inwards towards the axis. It is bounded on the inside by the potential core region and on the outside by a low velocity, low turbulence intensity, uniform air flow field. The rich premixture of propane and air has a fuel/air equivalence ratio of 10.4, which is well outside the limits of flammability so that the flame acts as a diffusion flame, dependent upon mixing with the surrounding air flow. The interface between fuel and surrounding fluid initially has a thickness dependent on molecular-diffusion. Flame stabilization occurs in the laminar mixing layer within 2 mm of the nozzle lip. The reaction zone is always within the interface where the mixture ratio is within the limits of flammability. Thus instabilities of the interface and vortex growth are visualized by the luminous reaction zone. When the jet and surrounding streams have low turbulence intensities, schlieren photography shows clearly the formation of distinct vortex rings by the rolling up of the initial laminar vortex sheet and it is known that the size and separation of these vortex rings can be artifically controlled by acoustic fields. The purpose of the present study is to

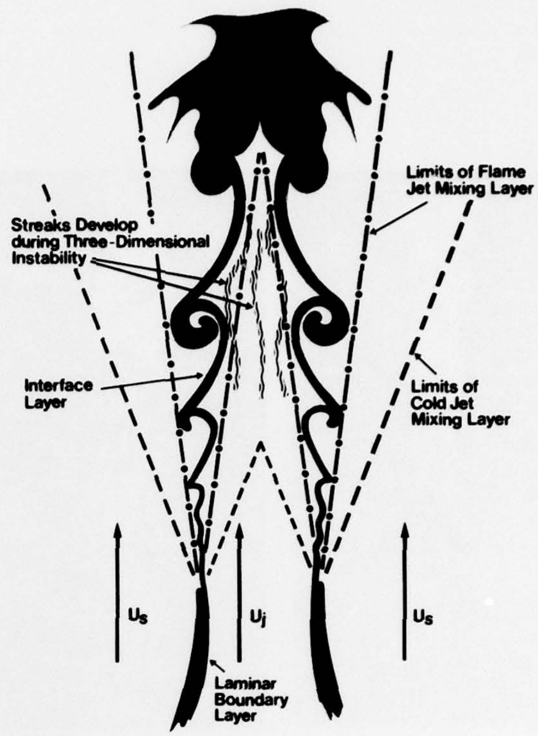


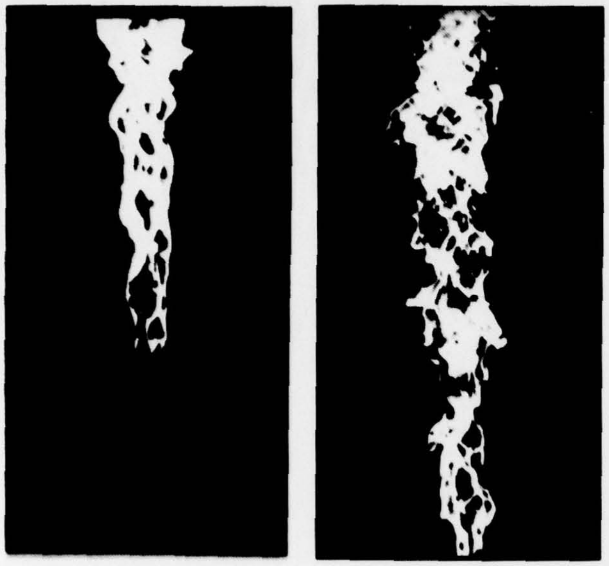
Fig. 2. Interface between jet and surrounding fluid in mixing layer of initial region of turbulent round jet.

examine the relationship between the physical structure of the mixing region under burning and non-burning conditions and determine the extent to which chemical reaction and heat release during combustion cause changes to the flow field and eddy structure.

Photographic Evidence

Figure 3 shows photographs of the flame with an exposure time of 1/500 s. Figure 3a shows the first 24 diameters of the jet flames. Ignition occurs at, or very close to, the lip of the nozzle and, for a distance of approximately 4 D, there is a relatively undisturbed cylindrical sheet of flame which must coincide with an undisturbed interface. Subsequently, the flame interface develops wave instabilities, curls up in scrolls and then rolls up to form ring vortices at about 10 D. This transitional flow is relatively orderly and periodic. Figure 3b shows the region of the flame between 24 and 48 D. Here the flame interface becomes more ragged and the flame appears to be 'nicked' into discrete 'chunks'. In some cases, completely dark zones can be seen across the whole jet, separating flame chunks. Distinct bulges are seen at regular intervals along the flame length. Even at 40 D, dark patches can be discerned within the general luminous flame. The spread of the jet flame (excluding the bulges) is only a few degrees.

Figure 4 shows a single frame made with the high-speed cine camera at 1000 fps. and shows the typical flame condition in the region 8-16D, In the axial direction, the jet is generally divided into short distinct flame regions



Figures
3(a) (left). Initial region of flame, $0 \rightarrow 24D$, showing breakdown of laminar interface and formation of eddies.

3(b) (right). Turbulent region of flame, $24 \rightarrow 40D$, showing transition of eddies with laminar interfaces to large-scale eddy flame structures.

Figure 4. Single frame from high-speed cine camera, 1000 fps, $8D < x < 16D$ showing separate ring vortex flames and streak formation.

separated by large dark regions. These correspond to the waves and vortex rings formed by the Kelvin-Helmholtz instabilities. The individual flame vortex rings are also broken up azimuthally into patches of light and dark, indicating that luminous burning is not taking place along the complete circumference of the vortex ring. These azimuthal burning regions do not vary randomly in position from one vortex ring to the next. Thus the regions of luminous burning in successive vortices create a series of axial streaks. The longest of these individual streaks can stretch between 4 and 20D. Further downstream the streak on an individual vortex increases in length. Initially they only have axial components but, subsequently, they can develop tangential components creating the impression of helices as the flame curls around the almost cylindrical jet of unmixed fuel. Figure 5 shows frames typical of conditions between 16 and 24D. A hollow cylinder flame region, completely dark on the inside and outside and with diameter only slightly greater than that of the burner, can be seen. The flame front appears undisturbed and laminar. Above this, a bulge of flame is seen with an outer diameter almost twice that of the cylinder of flame. The flame front has spread to form a much larger surface area but the reaction zone still remains concentrated around a distinct interface with no evidence of burning on the inside or on the outside. Above this bulge, the flame appears to be nicked as though it were squeezed between large cold air eddy structures. The flame surface appears to be smooth and laminar-like. There are significant differences in location of the bulges from frame to frame, as the eddies are convected downstream.

The sequence of frames between 16 and 24D shown, Fig. 5, demonstrate that the large outward bulges of flame which occur in this region are caused by the coalescence of the vortices clearly seen upstream (Fig. 4.)

This photographic study resulted in the important conclusion that all of the physical structures and events found in the transition of non-reacting round jets from laminar nozzle boundary layers[2], can also be clearly identified for the reacting case. These phenomena are:
(i) Wave instability of the initial laminar mixing layer leading to vortex growth.
(ii) Three dimensional instabilities of vortices, causing axial streaks in the flow.
(iii) Coalescence of distorted vortices resulting in outward bursts of fluid, formation of large turbulent eddies and establishment of fully turbulent flows.

From this photographic study, there is clear evidence that flame interfaces surround ring vortices and that these ring vortices directly evolve

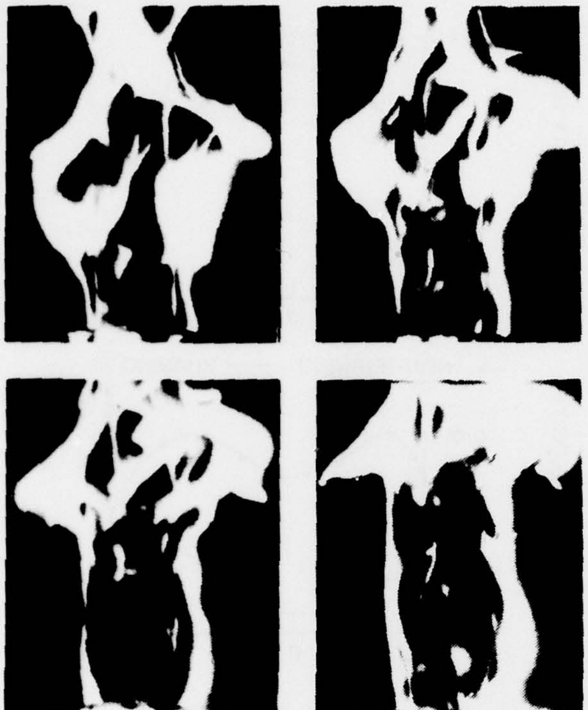


Fig. 5. Sequence of frames of region between 16 and 24D at 8 msec intervals.

into eddies in the downstream region. Changes in flame luminosity result from convolutions at the interfaces. For example, the luminous axial streaks indicate oxygen starvation due to the folding of interfaces accompanying three dimensional instabilities. The physical picture under flame conditions is thus very similar to that seen under non-burning conditions with one very important exception; the transition region is very much longer, extending to 20D rather than 3D for the cold case.

Passing Frequences of Vortices

Analysis of high-speed cine films in non-reacting jets have been made by Yule[2] , Browand and Laufer and others. Vortex rings were clearly seen in the regions where frequency halving was found in the measured power spectra. The average local passing frequencies of the vortices, as measured from the films [2], were within 5% of the local power spectra peaks. Vortex coalescing could be clearly seen and the average positions where coalescence occurred were the same as the positions where frequency halving was observed in the spectra. The coalescing of neighbouring vortex rings in the cold round jets was found to be similar to that observed for line vortices in two-dimensional mixing layers and is associated with enfulgment of potential-flow fluid in wedges between the vortices. Measurements for cold air jets are shown in Fig. 6. where the Strouhal number is plotted as a function of x/D; the Strouhal number $St(x) = FD/U_j$ was derived from the power spectra of axial velocity component measurements by hot wire anemometer where F is the peak frequency. The transitional flow can contain three vortex-coalescing regions, depending on the Reynolds number. These regions overlap in a given jet and there are no fixed values of x at which coalescence always occurs. The initial orderly, spiral interface between the jet and the entrained ambient fluid in the vortex becomes increasingly disordered and diffuse, as coalescence and engulfment proceed. Towards the end of the transition region, potential-core fluid and some fluid originally contained in the vortices, is ejected outwards between the vortices to form a diffuse layer at the outer part of the jet. This ejection corresponds to the radial bursts of flame in the burning jet.

Passing frequencies were measured directly from high-speed cine films in the flames and the calculated Strouhal numbers are shown in Fig. 6, where they are compared with the previous measurements of Yule in cold air jets. The cold flow data showed two distinct passing frequencies followed by a slow decay in the turbulent region. The high Reynolds number jet showed a continuous decay of St which is typical for a turbulent mixing layer. The flame passing frequencies show that, at 8D, St is 0.4 and this decreases due to coalescence and also deceleration of vortices. It can be concluded from this comparison that, at any given value of x/D,the separation distances between vortices are larger in the flame compared to the corresponding air jet. Coalescing in the flame also appeared to have considerable variation, and even periods without visible vortices could be discerned. The convection velocity for vortices in the flames was approximately $0.7\ U_j$, which is within the range of convection velocities of vortices in mixing layers of cold jets, as measured by several investigators. This is an important result as it indicates that buoyancy forces did not cause any significant acceleration of the vortices in the transition region. Thus the transition region in the flame is not significantly lengthened by buoyancy forces. The effect of combustion in lowering vortex passing frequencies and lengthening the transition distance can be explained by the increased damping and delay of decay due to the higher viscosity which can be considered roughly equivalent to a reduction in Reynolds number.

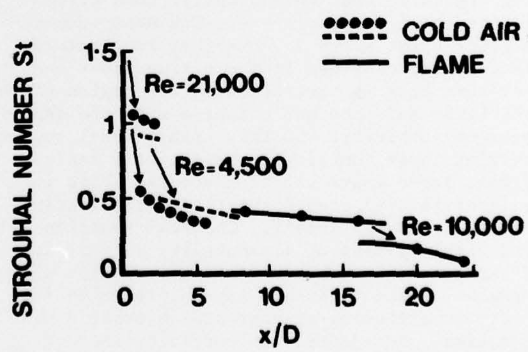


Fig. 6. Strouhal Number calculated from power spectra peaks in air jets and average vortex passing frequencies in flames.

Velocity and Temperature Measurements

A nozzle with a relatively large diameter has been selected in order to permit measurements with good spatial resolution in the initial, transitional and turbulent regions of the flame. Reasonably high Reynolds numbers can also be achieved with relatively low velocities. A Reynolds number, based on cold flow conditions at the nozzle exit, of 10^4, was chosen for the study reported in this paper. This provides an exit Reynolds number, based upon viscosity at flame temperatures,

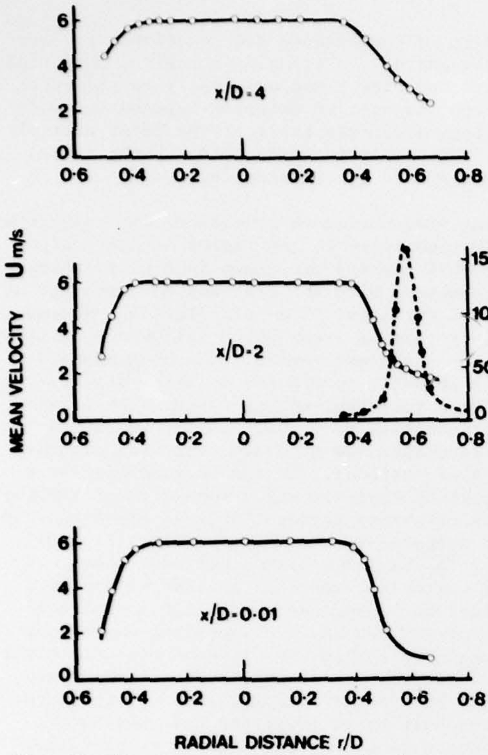


Fig. 7. Measurements of velocity by LDA and temperature by micro-thermocouple in initial region of flame.

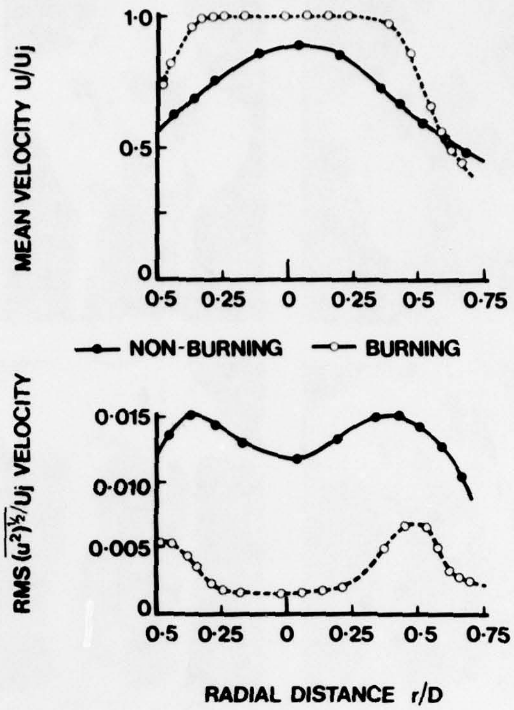


Fig. 8. Comparison of burning and non-burning flows at x/D = 4.

Re_f, of approximately 500. Measurements of mean velocity, $\bar{U}$, as measured by the laser anemometer in the flame, are shown at three axial stations corresponding to x/D = 0.12, 2 and 4 (Fig. 7). These measurements show a small increase in width of the mixing region so that the potential core still dominates the flow at x/D = 4. The mean temperature profile for x/D = 2 shows that temperature variations are confined to the mixing layer and the temperature peak is towards the outer region of the mixing layer and does not coincide with the region of maximum vorticity. In this transitional region the mixing layer contains an essentially laminar interface layer where reaction occurs. This interface layer is distorted by vorticity interaction and by the reaction itself. Chemical reaction only occurs within limits of flammability so that the peak temperature can be expected to coincide with the region of the interface layer into which fuel and air are diffusing at near stoichiometric mixture ratios. In addition to vorticity induced variations the locations of the stoichiometric regions of the flame will also be a function of the degree of premix in the nozzle fluid and the local diffusion coefficients, which are themselves affected by heat release. The inter-relationship between the temperature and velocity profiles will be studied in more detail.

The very significant differences between burning and non-burning flows in the initial region are clearly shown in Fig. 8, where mean and rms velocity distributions are shown at x/D = 4. For the non-burning je., the potential core is ended; the mean velocity on the axis is lower than the exit jet velocity and the mixing layer has spread across the whole jet. The rms velocity still shows peaks off the axis but turbulence levels in the central region are well above those at the nozzle exit. However, for the burning condition, the potential core is clearly evident and extends to r/D = 0.4. The rms values of velocity in the potential core region are unchanged from the nozzle exit conditions and the peak rms values in the mixing layer are only half those measured in the non-burning condition. This comparison shows that velocity decay, growth of the mixing layer, generation of turbulence and rates of entrainment, have all been very significantly reduced as a consequence of combustion. However combustion has not affected the potential flow of jet fluid but it has dampened the transition of the mixing layer flow to turbulence. It is noted that examination of the comparisons of the burning and non-burning flows in Fig. 8. could lead to the incorrect conclusion that combustion has accelerated the flow locally. In fact, in this transitional interface burning region, combustion has delayed the decay to turbulence which has the result that velocities can be higher locally for the burning than for the non-burning case, even though locally there is no significant temperature change.

Probability Distributions

An important link between the time-dependent changes and mean values is provided by probability density functions. Measurements made in the past of time averaged values of velocity, temperature and species concentration in flames have not been able to provide an explanation for unmixedness and other important time-dependent features of turbulent flames. Just as frame by frame analysis of the high-speed cine films showsqualitatively the relationship between instantaneous pictures and the long-time exposure photograph. It is essential

to interpret mean quantities in terms of physical descriptions of the fluctuating fields. This is specially true in flows where 'coherent structures' are known to be important. Thus, for example, in the transitional flame, mean quantities must be interpreted in terms of the signals produced by a continuous stream of discrete vortices. A key feature in the understanding of the interaction between turbulence and combustion is the probability density functions and joint probabilities and cross correlations of various quantities in flames. Measurement of probability density functions requires instruments measuring properties as a function of time with high-frequency response and sophisticated data processing. Both the laser anemometer and fine wire thermocouples are directly, and simultaneously, interfaced with a data analysis computer. Currently, the signal validation logic provides an accuracy of 0.5% in instantaneous velocity with an upper frequency response of 4k Hz. In fact with the comparitively low velocities used in this study the upper frequency is determined by the minimum obtainable time interval between individual instantaneous velocity measurements. This is dictated by the presence and passage of seeding particles through the measurement control volume, and also by the need to avoid multiple scattering of light.

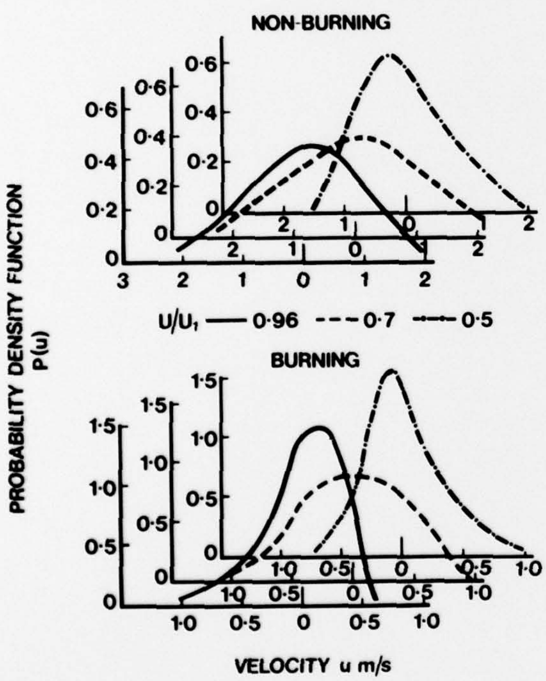


Fig. 9. Probability distributions of velocity at x/D = 4 for burning and non-burning flows.

The probability density functions for velocity at x/D = 4 are shown at three radial positions Fig. 9, where U/U_1 has values of 0.96 (edge of potential core), 0.7 and 0.5 (centre of mixing layer), where U_1 is the centre line velocity. The comparisons between burning and non-burning conditions have been made at radial positions, where values of U/U_1 are the same; this takes into account the large differences in thickness of the mixing layer under burning and non-burning conditions. It should be noted that the scales for both probability and velocity are different in the separate diagrams for burning and non-burning conditions of Fig. 9. The PDFs for the burning case are very much narrower than those for the non-burning case. The negative skewness on the inner (potential core) side and the positive skewness on the outer side of the mixing layer are more pronounced for the burning flow, perhaps reflecting the more regular and orderly eddies in the flame at this position. Skewness provides an indication of intermittency, so that entrainment for burning and non-burning flows appears to be significantly different.

Conclusions

The major physical processes of vortex formation and coalescence in the initial region of mixing layers of jets appear to be similar for cold and burning conditions. In both cases, wave instabilities develop in the laminar flow and vortices are formed which have significant periodicity. Coalescence of distorted vortices results in the establishment of turbulent flow and this can be identified by high-speed cine photography and from major power spectra. For Re of 10^4, coalescence in the flames occurs between 16 and 20D, compared with $x < 2D$ under non-burning conditions. Regions of flame luminosity indicate that reaction is occurring predominantly at interfaces which bound individual vortices. Wave instabilities in vortices are identified by luminous axial streaks. The luminous streaks mark the azimuthaly distributed troughs of ring vortices and are caused by quenching and/or oxygen starvation. Approximately 12 waves are seen to form around the circumference of the flame but the number of waves (and streaks) is a function of the Reynolds number. Downstream of transition detached islands of flame can be seen to be extinguished, due to detached fuel eddies, local quenching and local oxygen starvation.

Significant differences are measured in vortex passing frequencies and Strouhal numbers for burning and non-burning conditions. The high values of St between 1 and 2 in the first 2D of the non-burning jet are not detected under flame conditions. For the particular flame studied St is 0.4 at 8D and decays to 0.15. Coalescence is random in both cases but, in the flame, separation distances are larger, resulting in lower vortex passing frequencies.

Combustion causes temperature, density, viscosity, conductivity and molecular diffusion changes of the order of one magnitude. Buoyancy forces are generated, due to density differences and density change results in expansion, which must manifest itself in radial expansion and/or acceleration, so as to accommodate the increased volumetric flow rate. The results obtained from the present study suggest that the changes in kinematic viscosity have been the most important factor in the transitional flame in the very significant changes seen at Re = 10^4. The initial region is stretched in the axial direction from 3D to 20D. The potential core length is increased and the rate of growth of the mixing layer is reduced. This stretching is not due to increased convection speeds, but is caused by the delay in the establishment of turbulent flow. The fundamental mechanisms of potential flow, causing the roll-up of the interface, remains but, through the action of increased

kinematic viscosity, instabilities are damped. The net effect is roughly equivalent to reducing the Reynolds number. The detailed mechanisms of vortex growth and the physical structure of mixing layers in flames are being investigated in much greater detail.

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Acknowledgements

Financial support has been provided by the Office of Naval Research (Project SQUID), Sub-contract No. 8960-30), Air Force (AFOSR) Grant No. 77-3414, and the Science Research Council.

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4. TITLE (and Subtitle): THE PHYSICAL STRUCTURE OF TURBULENT FLAMES	5. TYPE OF REPORT & PERIOD COVERED: INTERIM
	6. PERFORMING ORG. REPORT NUMBER: 79-0217
7. AUTHOR(s): N A CHIGIER, A J YULE	8. CONTRACT OR GRANT NUMBER(s): AFOSR-77-3414
9. PERFORMING ORGANIZATION NAME AND ADDRESS: UNIVERSITY OF SHEFFIELD, CHEMICAL ENGINEERING & FUEL TECHNOLOGY DEPARTMENT, SHEFFIELD, S13JD, ENGLAND	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2308A2, 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BLDG 410, BOLLING AIR FORCE BASE, D C 20332	12. REPORT DATE: Jan 79
	13. NUMBER OF PAGES: 9
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

18 6 10 15 11 12 12p 16 2308 17 A2

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Aerospace Sciences Meeting, 17th, New Orleans, LA 15-17 Jan 79

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TURBULENT REACTING FLOWS	TURBULENT COMBUSTION
TURBULENT FLAME STRUCTURE	AIR-BREATHING PROPULSION
FLAME STABILIZATION	RAMJETS
FLAME PROPAGATION	GAS TURBINES
LASER VELOCIMETRY	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This paper reports on measurements made in the mixing region of an axisymmetric turbulent propane/air jet issuing from a round nozzle into a low-velocity, low-turbulence intensity, unconfined co-flowing airstream. The exit velocity of the jet fluid and its turbulence intensity are sufficiently low to allow the formation of ring vortices within the mixing layer, bounded, on the inside, by the potential core of the jet and, on the outside, by the secondary airstream. High speed cine films show evidence of formation of vortices and flamelets at the interfaces. The changes in shape, movement and coalescence downstream of the nozzle are over

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

examined. Measurements of fluctuating velocity are made by a single particle-counting forwardscatter laser anemometer. Fluctuating temperature is measured with micro-thermocouples with "in situ" measurement of time constant and direct compensation by digital signal recording and analysis. Variation in location and amplitude of peaks of velocity and temperature traces are directly associated with flame structures recorded by film. Signals from all probes are acquired and processed by PDP-8 and PDP-1103 Digital Equipment Corporation computers. Comparisons between cold and burning jets show that the essential physical processes of transition are the same for both cases, i.e. vortex growth, coalescence, three dimensional breakdown and turbulent large eddy formation. The major effect of combustion in the intial region is increased viscous damping of interface instabilities which greatly increases both the transition and potential core lengths of the jet.